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ATTENUATION OF EARTH PRESSURES INDUCED BY AIR BLAST

William R. Perret, Division 5111

March 7, 1952

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AFSWP ltr. dtd. 7-11-58
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ACKNOWLEDGEMENT

Measurements of air-ground pressure coupling and earth-pressure attenuation were suggested by E. F. Cox and were conducted under his general supervision and the direct supervision of B. F. Murphey. The plans were developed by W. R. Perret and B. F. Murphey and were reviewed by W. E. Ogle, F. B. Porzel, and E. J. Zadina of Los Alamos Scientific Laboratory.

Measurements at the Buster Site were made by Proving Ground Department of Sandia Laboratory under the supervision of H. E. Lenander and R. S. Millican. Gauges and recording equipment were installed and operated by George Reis, O. K. Kowallis, V. V. Myers, Allen Korbe, ETS, USN, and William Payne, RD, USN.

Data were processed from field records to tabular form by the Test Data Department of Sandia Laboratory.

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ATTENUATION OF EARTH PRESSURES INDUCED BY AIR BLAST

Summary. -- Measurements of air-blast pressures and earth pressures induced by air blast from the airburst bombs of Operation Buster are described. Graphs of the pressure-time data derived from the air-pressure gauge and earth-pressure gauges at four depths are presented. Certain factors which have made the data questionable quantitatively are discussed. The principal findings are that the induced ground pressures are possibly somewhat greater than the air-blast pressures, and that the attenuation factor of the earth pressure between the 5- and 20-ft depths may be as much as 2.

Purpose and Scope of Tests

The effectiveness of earth cover as a protection against air blast for either subsurface or above-surface structures is a factor of structural design concerning which little or no quantitative data are available. It has seemed likely that with quantitative knowledge of the protective effects of earth cover it might be possible to design structures more economically, or at worst, to be reasonably sure that structures were not grossly overdesigned. Reasoning of this nature led to the inclusion in Operation Buster of a special installation of earth-pressure gauges at Station D on the 600 blast line. The installation was designed to give data concerning the air-to-ground coupling of the blast pressure and attenuation of the vertical component of earth pressure with depth.

Limitations of time and recording facilities confined instrumentation for this purpose to a single location. Plans called for measurement of air pressure at the ground surface and of vertical stress in the soil at four depths, of which three were within an artificial fill of considerably greater lateral extent than the gauge array. Data were expected to provide information of a preliminary nature concerning both air-to-ground blast-pressure coupling and depth attenuation of induced earth stresses and indications of the adequacy of placement procedures for this type of measurement. It was understood that such data as were obtained would be applicable directly only to the particular soil or very similar soils and would require amplification by more comprehensive tests for this and other soil types if the data were to be made generally applicable.

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Instrumentation

The end instruments used in this study included a Wiancko air-pressure gauge and four Carlson-Wiancko earth-pressure gauges. The output of these instruments was fed through approximately 3000 feet of cable to a Consolidated Engineering Corporation System D carrier-amplifier and recorder in a concrete underground shelter.

The surface air-pressure gauge, DS, was a unit of the time-distance airblast measurement array. It was located at approximately 1,200 feet from the nominal ground zero for Shots Baker, Charlie, and Dog. The precision and performance of this gauge and other of the airblast array are discussed in WT-304. The over-all error estimated for this gauge is from 10 to 20 per cent.

The earth-pressure gauges were placed at four depths: 1, 5, 10, and 20 feet below the ground surface at a point approximately 20 feet west and 8 feet north of DS. These gauges as normally calibrated on their respective recorder channels would be expected to have a precision of the order of 5 per cent. However, an exceedingly tight time schedule prevented calibration of the three deeper gauges in the normal manner. An alternative calibration procedure was adopted in which the shallow 1-ft depth gauge, D0, was connected to each channel and calibrated with proper phase balancing. The data from each of these calibrations, corrected for the ratio between the static calibration of D0 and each of the deeper gauges, were substituted as the calibration of that gauge on its assigned channel after suitable phase balancing. It was originally intended that this should be a secondary calibration to be verified or corrected by a post-test calibration of the customary sort. However, the need for the recorder equipment for later tests, and contamination in the vicinity of the gauges, prevented the post-test calibration. The substitution calibration was therefore used in reduction of the recorded data. An attempt was made at a later date to determine the proper calibration response for these gauges, but the results were inconclusive except to establish that for the shallow gauge, D0, the calibration precision is probably 5 per cent but that for the deeper gauges the substitution method introduced a possible total calibration error of from 50 to 100 per cent. In addition to these errors, the error caused by local variations in the soil surrounding the gauges and in the density of the backfill in general was probably greater than usual in this installation because of absence of adequate and uniform compaction. This error was probably between 25 and 50 per cent. The precision of the earth-pressure measurement may thus be no better than 75 to 150 per cent for the three deeper gauges, D5, D10, D20. The over-all precision for D0 is probably also in this range because of extreme soil conditions.

The set ranges for DS for each test, described in WT-304, were used as the basis for determining the set ranges for the earth-pressure gauges. It was apparent that only one set of gauges could be used for all five shots so that the design range of the gauges, 180 psi, was selected to accommodate the maximum expected pressure of 150 psi. This meant, of course, that for some of the shots set ranges would be well below the design range of the gauges. The set ranges of D0 and D5, 1 and 5 feet deep, were chosen equal to those for DS; those for D10, 10 feet deep, were made 2/3 of the DS set range and those for D20, 20 feet deep, were set at half the DS range. The anticipated air-blast pressures at Station D were so low for the Able test that all four earth-pressure gauges were given the same set range, 2 psi. This range was such a small portion (about 1 per cent) of the usable range for the gauges that some doubt existed concerning the value of the data obtained. Although the laboratory calibration over the 2-psi range was linear, circuit noise in the records for Shot Able was in some instances nearly equal to the set range.

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The actual set ranges used were usually lower than the estimated values because of the lower yields and lower pressures observed during the Buster tests. The set range estimates were adjusted prior to each test so that the instruments could be used to the optimum extent.

Placement of Instruments

The air-blast gauge, DS, was placed with its opening flush with the ground surface. The gauge was mounted in a 2-ft cube of concrete surrounded by a circular area of bituminous pavement of 10-ft radius. Its location and that of the earth-pressure gauges are shown with respect to the several ground zero points in Fig. 1.

The earth-pressure gauges were located in a vertical array in an excavation near Station D of the blast line.

The excavation consisted of a pit 12 feet deep dug by a bulldozer operated in a north-south direction across the blast line. The east-west bottom width, determined by the width of the dozer blade, was about 8 feet. The east and west walls were nearly vertical, and the north and south ends of the pit had slopes of about 35 degrees. At the bottom of the pit, a hole 15 inches in diameter was bored with a power auger to a total depth of 21 feet below the ground surface. Details of the placement of these instruments are shown in Fig. 2.

The boring was backfilled with dry sand to a depth of 20 feet below ground level. This sand was dropped into the hole without tamping. The gauge, D20, was placed at the prescribed depth and was observed to be level within a very few degrees. The remainder of the hole was backfilled with sand dropped in but untamped. Placement of the gauges within the pit followed a different procedure. The gauges were placed on a mound of tamped dry sand and covered with hand-tamped sand to a depth of about 1 foot. Random fill was placed and tamped by hand to a depth of 1 to 2 feet around the mounds containing the gauges. A bulldozer was used to place and tamp the bulk of the fill between gauge levels. Care was exercised during placement to ensure that the gauge face plates were horizontal within 3 degrees.

Presentation of Results

Data were obtained from each of the five gauges of the earth-pressure coupling and attenuation instrumentation at Station D during Buster Shots Able, Baker, and Charlie and from DS, D5, and D20 during Shot Easy. No data were derived from Shot Dog because of a 5-sec delay in the recorder start-up timing signal. These data, in the form of oscillograph records, were reduced by means of precise reading devices to tabulations of pressure as a function of time for each gauge on each shot. Curves were plotted from these data and various parameters derived from the curves. Certain of these parameters, including arrival times and duration and peak pressure of the positive phase for all the recorded data, are presented in Table I. No data were obtained from D0 during Shot Easy because the recorder channel for that gauge on previous tests was required for special instrumentation on the final test. The recorder channel to which D10 was connected failed to respond during Shot Easy, and no data are available from it for that test.

Families of pressure-time curves for Shots Baker, Charlie, and Easy are shown in Figs. 3, 4, and 5, respectively. The graphs include the data from the surface gauge, DS, and

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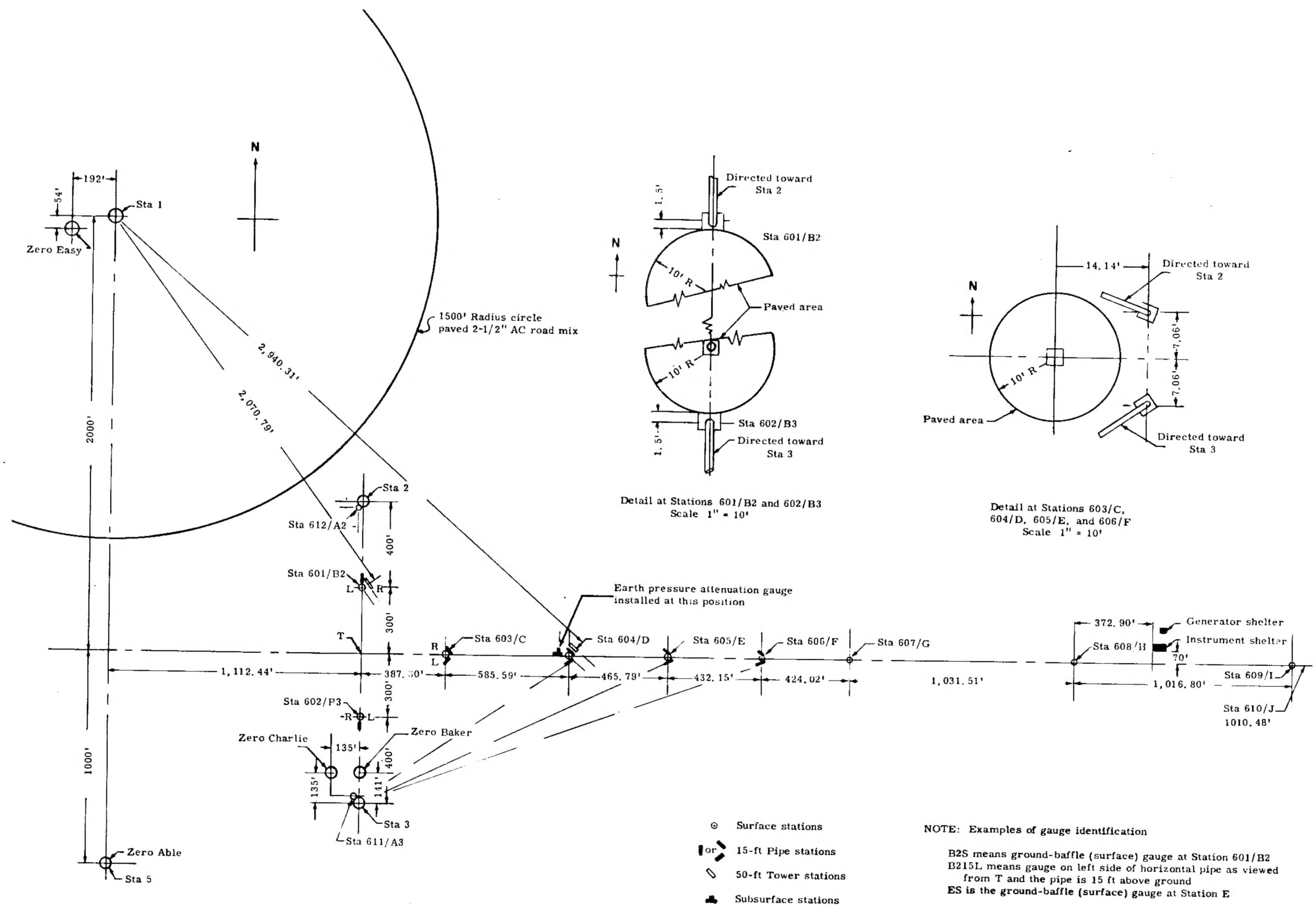

Fig. 1. -- Site plan

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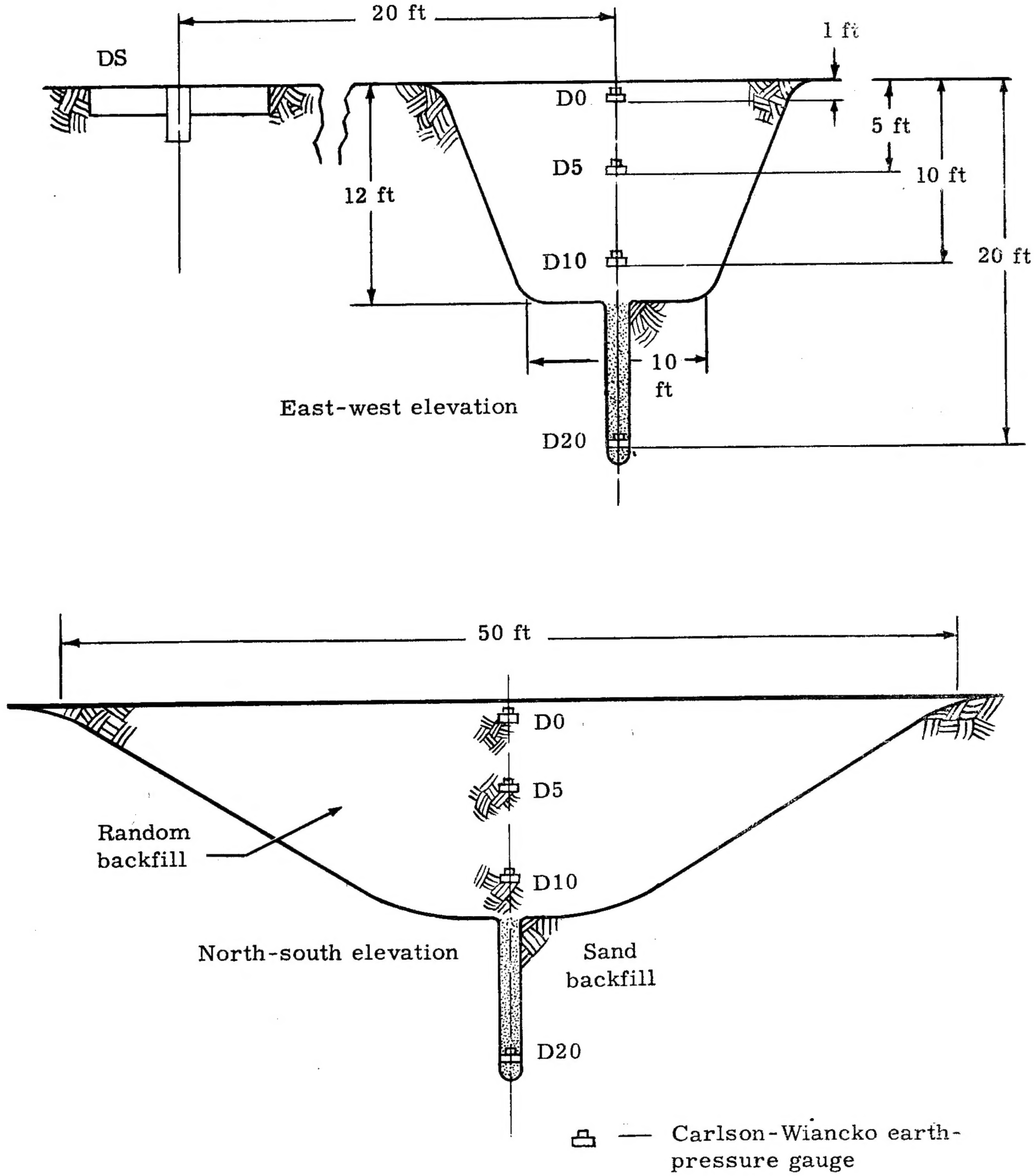

NOTE: Excavation by bulldozer and power auger, random backfill, hand-placed and hand-tamped in vicinity of gauges

Fig. 2. -- Earth-pressure gauges -- Operation Buster -- Station D -- 600 blast line

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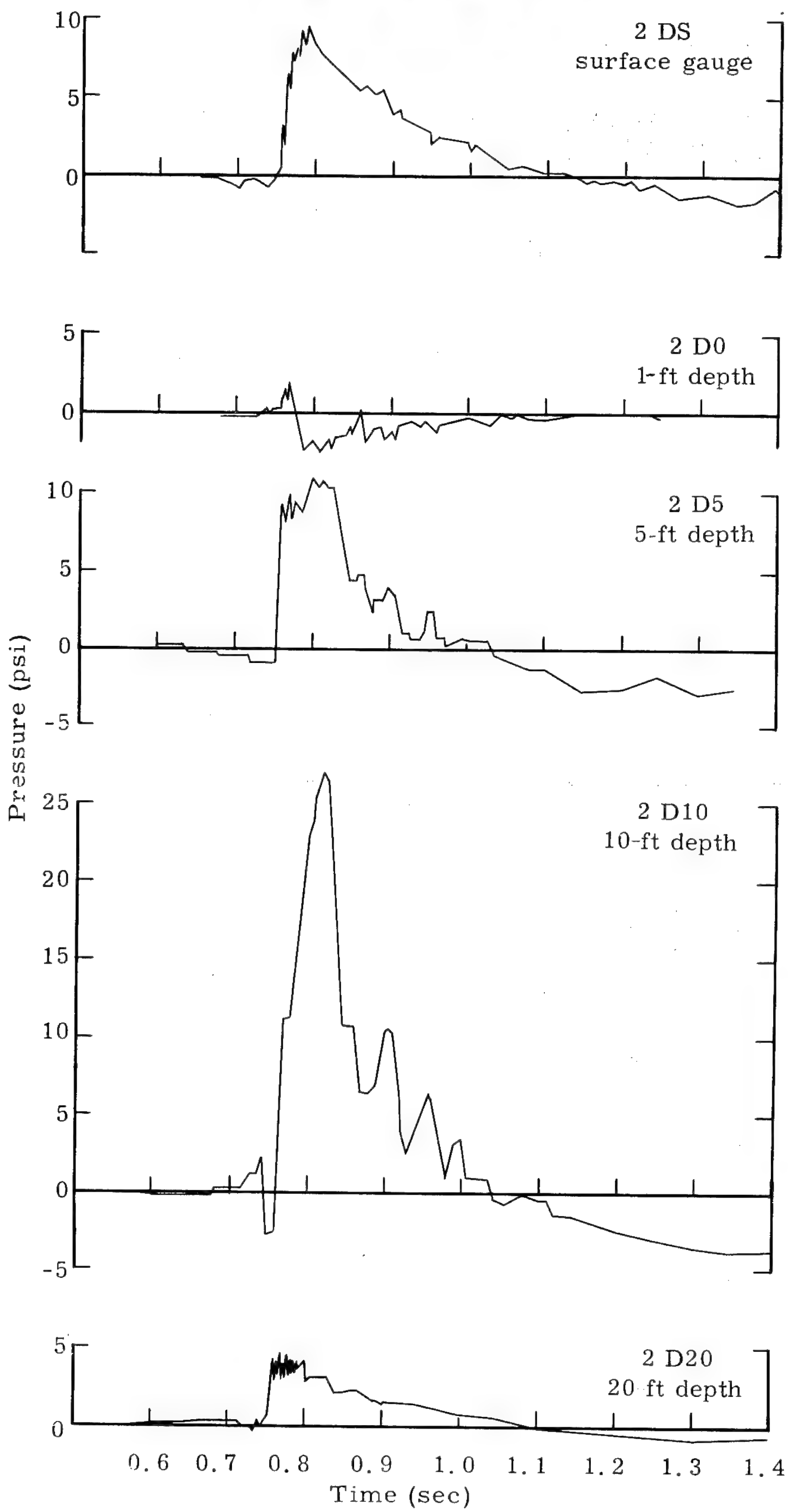

Fig. 3. -- Pressure-time curves from earth-pressure gauges at 1,123 feet from ground zero (Buster Shot Baker)

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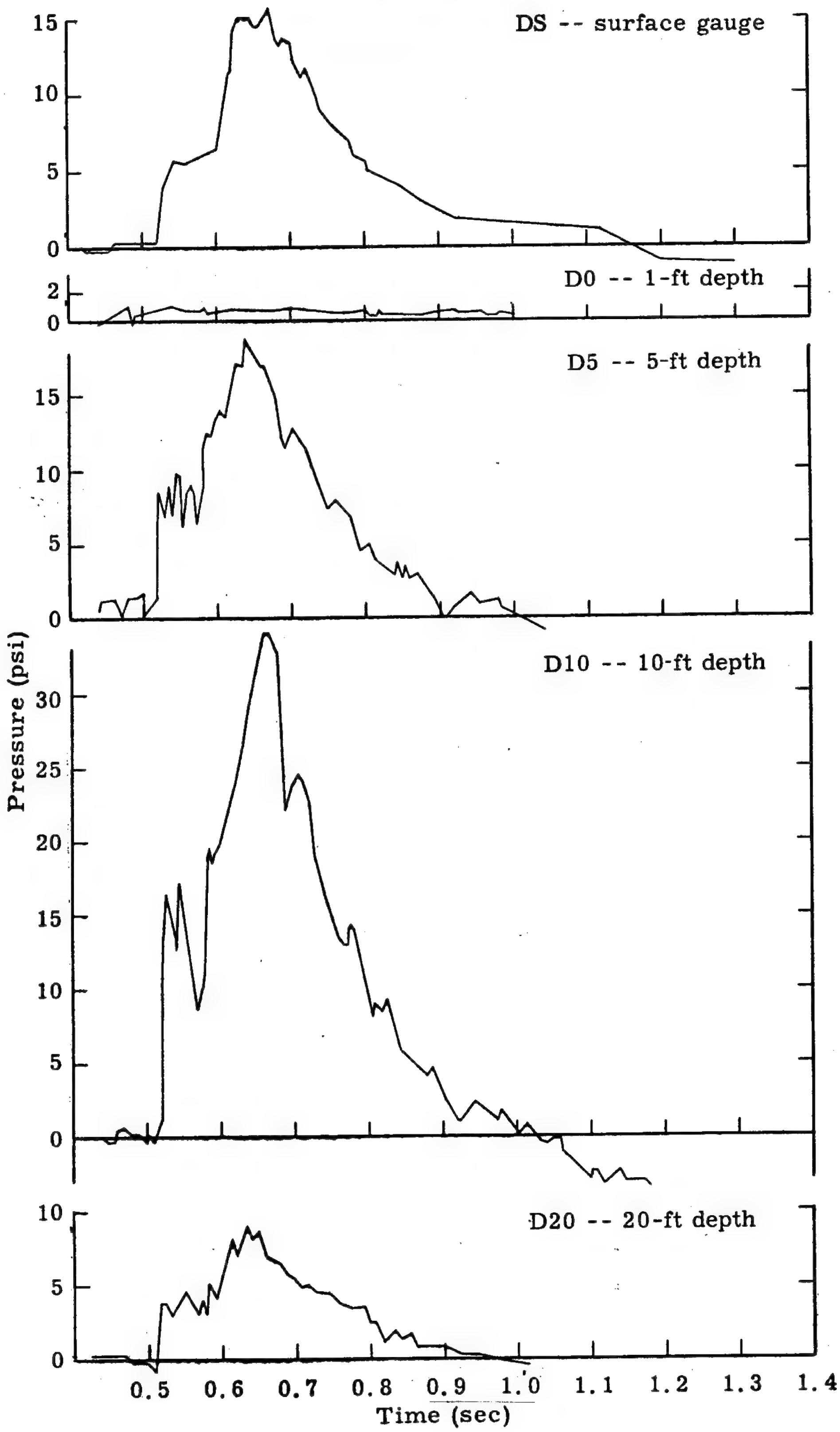

Fig. 4. -- Pressure-time curves from earth-pressure gauges at 1,245 feet from ground zero (Buster Shot Charlie)

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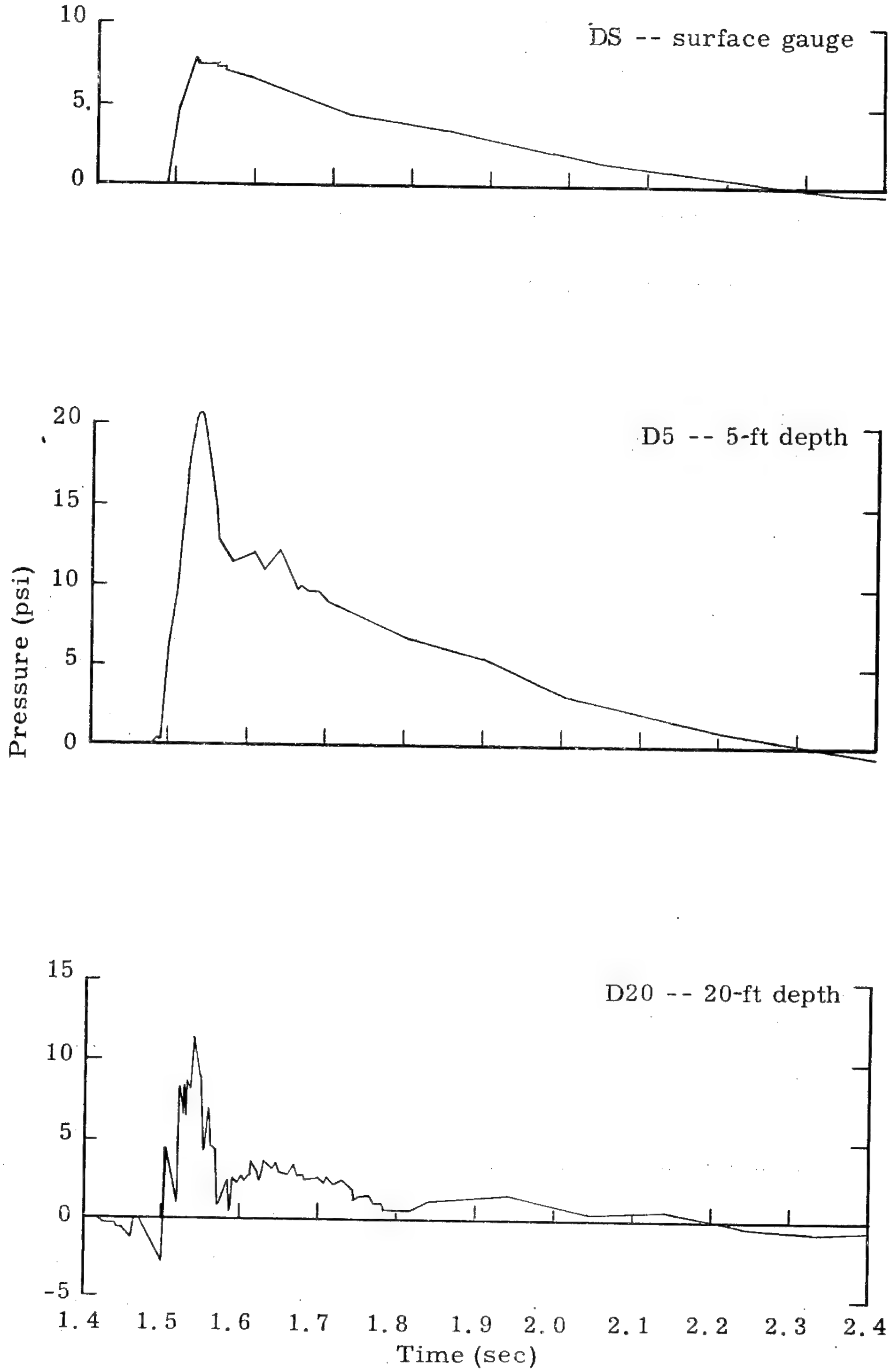

Fig. 5. -- Pressure-time curves from earth-pressure gauges at 2,910 feet from ground zero (Buster Shot Easy)

from each of the earth-pressure gauges at Station D for which usable records were obtained. All graphs are plotted on the same pressure and time scales, but the time scales are shifted to compensate for differences in arrival times resulting from differences in the slant distance for the several shots. In a few instances, minor sharp peaks in the recorded data have been omitted from the graphs because of irrelevance and difficulties in reproduction. The curves derived from Shot Able data are not included in this report because the recorded pressures were so low as to be adversely affected by circuit noise and similar extraneous factors.

TABLE I

Results of earth-pressure attenuation measurements

Shot	Gauge No.	Gauge Depth (ft)	Arrival time (sec)	Positive phase Duration (sec)	Positive phase Peak pressure (psi)
Able	DS	surface	2.02	0.094	0.42
	D0	1	2.03	-	0.03
	D5	5	2.03	0.108	1.0
	D10	10	2.03	0.130	1.7
	D20	20	2.03	0.127	0.82
Baker	DS	surface	0.756	0.366	9.2
	D0	1	0.751	0.349	2.2
	D5	5	0.756	0.276	10.8
	D10	10	0.761	0.282	27.0
	D20	20	0.751	0.349	4.1
Charlie	DS	surface	0.517	0.638	15.6
	D0	1	0.504	0.579	1.1
	D5	5	0.510	0.483	18.9
	D10	10	0.514	0.516	34.0
	D20	20	0.510	0.468	8.8
Easy	DS	surface	1.488	0.806	7.9
	D0	1	-	-	-
	D5	5	1.485	0.855	20.6
	D10	10	-	-	-
	D20	20	1.497	0.661	10.5

Results

The shape of the pressure-time curves obtained from the deeper earth-pressure gauges at Station D for each shot corresponds very closely with that of the air-blast curve obtained from DS. Notable exceptions are the records from the shallow gauge, D0, which indicated response of the gauge to much lower pressures than those indicated by either DS or D5, above and below it. The graphs plotted from the Shot Charlie data for DS show the presence of a step or plateau of about 50 msec duration within the rising portion of the positive phase. This plateau has a pressure value of about 40 per cent of the peak positive phase pressure. Graphs

for the three deeper earth-pressure gauges, D5, D10, and D20, show a similar plateau of about 50 msec duration and at a pressure level of about 50 to 60 per cent of the peak pressures. This coincidence and similar coincidence of several minor anomalies on the pressure-time curves for all gauges except D0 indicate that the earth pressures measured are those induced by the air blast which impinges on the ground surface.

Arrival of the shock front at each gauge, indicated by the arrival times in Table I, is significant to this study only in identifying timewise for each gauge the pressure source with the same actuating phenomenon -- the air blast at the ground surface over the gauges. There are inconsistencies in this information, such as arrival of the initial impulse at some of the deeper gauges earlier than at the surface or shallow gauges. These time differences are 5 to 10 msec or less and may result from arrival of the shock front at different gauges either over slightly different paths through the soil or from adjacent points on the ground surface. However, in view of the marked similarity in the shapes of pressure-time curves previously discussed, a more valid reason for the discrepancies may be inaccuracies in picking precise arrival times, caused by circuit noise or the absence, in some instances, of well-defined zero pressure levels. No consistent pattern appears to exist in the relation of gauge depth and positive phase duration. Low precision of this measurement, however, indicates that this inconsistency may have resulted principally from uncertainties in identifying the after end of the positive phase. Irregularities of the recorded data and flatness of the slope in this portion of the recorded curve decrease the precision to the point where tens of milliseconds may be irrelevant. These data indicate, in general, positive phase durations of similar magnitude for each shot, increasing with increased distance from ground zero. There seems to be some tendency toward decrease of the positive phase duration with depth, but the data are not sufficient in number or consistency to establish the trend definitely.

The peak pressures of the positive phase, included in Table I, are the data which serve as criteria of air-ground coupling and earth-pressure attenuation. The foregoing discussions have served to establish that the pressures recorded by the earth-pressure gauges are those induced by the air blast at the ground surface in the immediate vicinity of the gauge array. The peak pressures recorded by each gauge for a specific shot occurred, as indicated by the graphs, at essentially the same part of the positive phase for all gauges. They should therefore be comparable and pertinent as measures of air-ground coupling or earth-pressure attenuation.

The peak pressures recorded by the vertical array of gauges follow a similar pattern for each shot. D0, at a depth of 1 foot, indicated peak pressures lower than DS peak air pressures by a factor of 4 to 14. D5, at a depth of 5 feet, indicated peak pressures for Shots Baker and Charlie that were 10 to 20 per cent higher than the DS peak air pressures. The D5 peak pressures were about twice the DS peak air pressures for Shots Able and Easy. Peak pressures indicated by D10, at a depth of 10 feet, were from 2 to 4 times the peak pressures indicated by the DS and D5 gauges. Finally, D20, at a depth of 20 feet, indicated peak pressures which were consistently about half the D5 peak pressures except for Shot Able data, when the factor was 0.8.

These data are, of course, affected radically by the gauge calibration and by the manner of placement and condition of backfill material. The DS data are certainly the most reliable and, from the standpoint of precision of calibration as well as location, can serve as a suitable basis for comparison with the earth-pressure data to indicate air-ground coupling and earth-pressure attenuation. The D0 data, which were expected to provide the most pertinent information for determination of air-ground coupling and a basis for earth-pressure attenuation, were wholly unreliable. This reaction probably resulted from the nature and density of the soil beneath the gauge. The small overburden load, about 0.4 psi, was insufficient to produce adequate shear strength in the soil below the gauge to prevent movement of the gauge when

pressures of 1 to 2 psi were exerted at the surface. Essentially this means that minor shear failures developed and permitted the gauge to move with the load, thus preventing registration of the pressures greater than those which caused the excess shear loading or transition to plastic deformation. This condition existed in all tests. Whether it could be prevented by increased soil compaction near the surface might be questionable because of the very loose floury nature of the soil, particularly after it has been disturbed.

Data from D5 are more usable than those from D0 although they are of considerably lower precision. The Baker and Charlie data from D5 suggest that the air-ground coupling may be one-to-one. Data from Shot Easy suggest that the ground pressures may be the greater. However, consideration of the magnitude of possible errors in the D5 data does not permit very useful prediction of a coupling factor. It is possible that the generally loose condition of the backfill, as noted on inspection after removal of the gauges, might have introduced a minimum of attenuation between the air-blast pressure and soil at the 5-ft depth. However, the fact that all D5 peak pressures are greater than the DS peak values and that the low soil density would tend to cause the gauge to underregister suggests that the air-ground coupling factor may be greater than 1. Whether this means by a matter of a few tenths or a factor of two can not be estimated from the available data.

The peak pressures at the 10-ft depth appear to be anomalous. The fact that these pressures are 2 to 4 times those given by the surface and the 5-ft gauges and the evident identitiy of the actuating phenomenon for all three instruments does not agree with expected attenuation with depth. The data contain no obvious explanation for this anomaly. It is possible that to some extent it may have been caused by the calibration procedure used, but the effect appears to be too large to attribute entirely to calibration sources. It is also possible that reflection and focusing effects involving the looser backfill material and the more dense undisturbed soil surrounding the pit may have produced the high pressures to which the gauge evidently responded. However, in the absence of a more effective explanation, the anomalous character of the data from D10 make it suspect.

Peak pressure data from D20 show evidence of attenuation by a factor of about 2 below those for D5. The general characteristics of the data from this study make it difficult to determine to what extent the data which trend in the anticipated direction may be reliable. The position of D20 and its method of placement tend to give it somewhat more reliable response than the shallower gauges. Its calibration is doubtful to the same extent as that of D5 and D10 It is probably reasonable to evaluate the attenuation factor between the 5-ft and 20-ft depths as not greater than 2. If reflections such as those postulated to explain the anomalous pressures at D10 do occur, these may also account for a part of the decrease in the D20 pressures from those shown at D5.

To summarize this discussion it can be said that except for DS the data are relatively unreliable. Data from D0 are completely doubtful and must be ignored in the determination of either coupling or attenuation factors. Data from D10 are also suspect, and in view of the evidence of attenuation in the D20 data, those from D10 should also be ignored in determination of attenuation factors. The data from the 5-ft depth suggest that the coupling factor for air-induced earth pressures is 1 or slightly greater. Comparison of data from the 5- and 20-ft depths indicate an attenuation of 2 or somewhat less. Data from Shot Able, although included in Table I, are not reliable and do not merit consideration for either the coupling or attenuation problems.

Conclusions and Recommendations

The measurements to determine air-ground coupling of the blast pressure and attenuation of the earth pressure induced by air blast from an airburst were inconclusive in a strictly quantitative sense as a consequence of the uncertainties inherent in the calibration procedures used. Conclusions of a semiquantitative nature may be derived from the results of the tests.

Air-to-ground coupling of blast pressures is at least one-to-one, and somewhat higher earth pressures may be induced by the air blast.

Earth pressures induced by air-blast pressure are attenuated by a factor of about 2 or less in the first 20 feet of depth.

These conclusions are of little use for ultimate design of earth-cover protection, but they emphasize the facts brought out in discussion of the data which must be given consideration in the conduct of future tests of a similar nature.

Certain recommendations pertinent to the conduct of tests to determine air-ground coupling and attenuation of induced earth pressures are presented to facilitate planning of such future test programs.

Calibration of the individual gauges through the assigned recorder channels and cables is recommended to remove the doubt implied by the possibility of low precision introduced by substitution procedures of calibration.

Placement of the gauges and backfill must be made in such manner as to ensure soil densities equal to or slightly greater than those of the surrounding soil. Compaction should always be made on lifts of 8- to 10-in. thickness, never in thicker lifts since semicompacted or uncompacted layers are left at the base of each of the thicker lifts. It is considered preferable wherever feasible to place the gauges in pits excavated in the fill to the specified gauge elevation after the fill has been compacted mechanically to a grade about 2 or 3 feet above the gauge level. This procedure increases the chance for uniformity of backfill density.

It is realized that the uncertainties evident in the test results may not be solely the result of the calibration procedure or gauge placement. It is perhaps equally possible that except for the gauge at the 1-ft depth the pressures indicated are the true pressures within reasonable accuracy and that the apparent anomaly at D10 was due to some unexplained phenomenon. It is recommended, therefore, that further tests to determine both the air-ground coupling and earth-pressure attenuation be made, using different types of installation. One such installation would involve placement of gauges in individual holes at several depths to a maximum of 20 feet and spaced laterally at 10-ft intervals. Another type of installation which should be tested involves placement of gauges at various depths within a mound composed entirely of compacted soil having side and end slopes sufficiently gentle to prevent the formation of strong vortices. An air-pressure gauge flush with the top of the mound or mounted to read side-on pressures directly above the mound would furnish a basis for establishing the source of the indicated pressures and for air-ground coupling determination.

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